AD NUMBER
AD816988
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies and their contractors; Critical Technology; FEB 1967. Other requests shall be referred to Office of Naval Research, Field Projects Branch, Washington, DC 20360. This document contains export-controlled technical data.**
AUTHORITY
per onr ltr, 28 jul 1977

SU-SEL-67-026

AD816988

Computer Prediction of the Effects of HF Oblique-Path Polarization Rotation With Frequency

by

M. R. Epstein

February 1967

Technical Report No. 139

Prepared under
Office of Naval Research Contract
Nonr-225(64), NR 088 019, and
Advanced Research Projects Agency ARPA Order 196-67

RADIOSCIENCE LABORATORY

STANFORD ELECTRONICS LABORATORIES

STANFORD UNIVERSITY · STANFORD, CALIFORNIA

SEL-67-026

COMPUTER PREDICTION OF THE EFFECTS OF HF OBLIQUE-PATH POLARIZATION ROTATION WITH FREQUENCY

by

M. R. Epstein

February 1967

Technical Report No. 139

Prepared under

Office of Naval Research Contract
Nonr-225(64), NR 088 019, and
Advanced Research Projects Agency
ARPA Order No. 196-67

Radioscience Laboratory
Stanford Electronics Laboratories
Stanford University Stanford, California

ABSTRACT

When a CW skywave signal is received on a linearly polarized antenna, polarization (Faraday) rotation produces a variation of received signal strength with radio frequency. The resulting dependence of received signal amplitude on radio frequency imposes a bandwidth limitation on pulsed signals transmitted over ionospheric paths. A measure of this limitation, termed "coherent polarization bandwidth," is defined to correspond to the bandwidth in which the plane of polarization rotates 90°.

Computer raytracing calculations were performed using a single Chapman-layer ionospheric model to determine the one-hop coherent polarization bandwidth as a function of geomagnetic azimuth and frequency. The coherent bandwidth was found to decrease with increasing path length, radio frequency, and geomagnetic azimuth. Assuming a critical frequency of 9 MHz and a path length of 2000 km, the bandwidth increased from a minimum of 140 kHz at 10.5 MHz and from a minimum of 70 kHz at 17.5 MHz as the propagation direction varied from geomagnetic north to east.

The theoretical effects of polarization rotation with frequency, and also of ionospheric dispersion or phase distortion, on the envelope shape of short-pulse signals (of from 0.5 to 50 μs duration) were calculated by computer for the same path. A pronounced waveshape distortion due to the effect of polarization rotation on the pulse envelope was observed when the signal bandwidth appreciably exceeded the coherent polarization bandwidth for the path.

CONTENTS

ILLUSTRATIONS

ACKNOWLEDGMENT

The author wishes to thank Mr. Douglas Westover for programming the computer to determine the pulse envelope shapes; Dr. O. G. Villard, Jr. for his guidance and assistance; and Dr. John M. Kelso (of ITT Electro-Physics Laboratories) for his helpful suggestions.

I. INTRODUCTION

The purpose of this study is to investigate polarization rotation (frequently called Faraday rotation) as a function of frequency and to determine its effect on HF communications. When a CW skywave signal is received on a linearly polarized antenna, polarization rotation produces a variation of signal strength with radio frequency. Polarization rotation with frequency--as well as the more commonly observed polarization rotation with time--is due to magnetoionic splitting of the radio wave in which two components result: one ordinary and the other extraordinary, both of roughly equal amplitude [Refs. 1, 2]. In the case of polarization rotation with time, changes in the ionospheric electron density and slow internal ionospheric motions result in a variation of the phase path difference of the two circularly polarized components with time. In the polarization rotation with frequency case, however, the relative phase between the extraordinary and ordinary components varies with frequency so as to produce a linearly polarized wave whose plane of polarization rotates with frequency. Such a wave interacts with a linearly polarized receiving antenna to produce signal amplitude variations with frequency. The resulting amplitude-frequency characteristic can be detrimental to the transmission of broadband and/or short-pulse signals over an ionospheric path.

In Section II, raytracing calculations are employed to determine the rate of polarization rotation with frequency for one-hop communication as a function of both frequency and the angle the raypath makes with the earth's magnetic field. These results are employed in Section III to determine the effect of polarization rotation with frequency on the envelope shape of short-pulse signals reflected from the ionosphere. Section IV is a discussion of a figure of merit that a communications designer might employ in considering the effect of polarization rotation with frequency over a given communications link. Several techniques that might be employed to remove the effects of polarization rotation are also considered.

II. POLARIZATION ROTATION RATE AS A FUNCTION OF FREQUENCY

Polarization rotation can be predicted by the use of the magneto-ionic equations. The polarization tilt angle ψ in cycles is given by

$$\psi = \frac{1}{2}(P_o - P_x)$$

where P_o and P_x are the phase path lengths (in wavelengths) of the ordinary and extraordinary waves, respectively.[3]

$$P_o = \frac{1}{\lambda}\int \mu_o \, ds \qquad P_x = \frac{1}{\lambda}\int \mu_x \, ds$$

where λ is the free-space wavelength and μ_o and μ_x are the indices of refraction for the two magnetoionic components for longitudinal propagation. The integral is taken over the raypath.

$$\mu_{\substack{o\\x}} = \left(1 - \frac{X}{1 \pm Y}\right)^{1/2}$$

where

$$X = \frac{f^2_{plasma}}{f^2} \quad \text{and} \quad Y = \frac{f_{gyro}}{f}$$

For quasi-longitudinal propagation, Y is replaced by Y_L, the longitudinal component of Y. This is valid for propagation angles of up to more than 80° away from the direction of the magnetic field. At the receiving antenna,

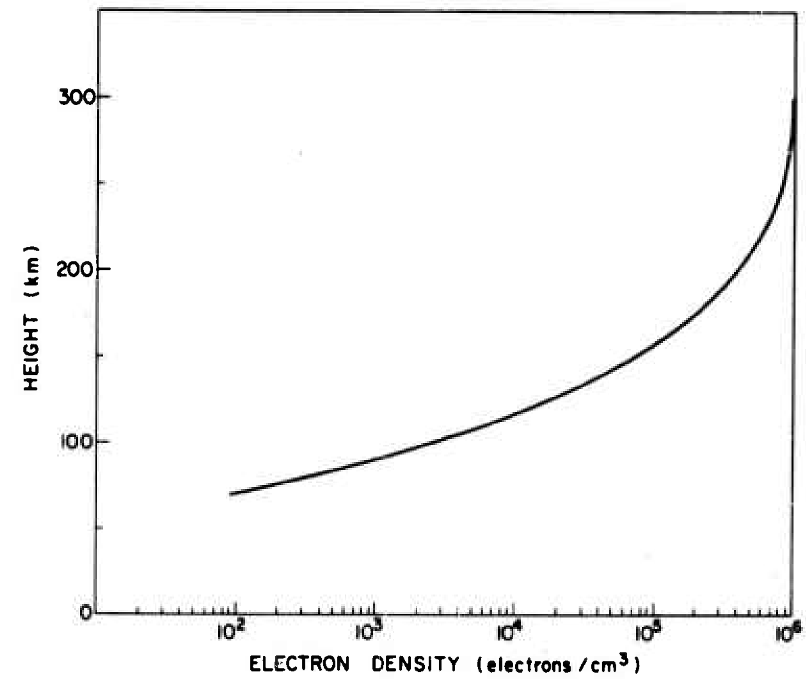
$$\psi = \int_{path} \frac{\omega}{2c}(\mu_o - \mu_x)\, ds \tag{1}$$

where ω is the wave frequency and c is the speed of light in free space. For a given instant of time, Eq. (1) indicates that the incoming polarization angle is a function of frequency and raypath alignment with the magnetic field.

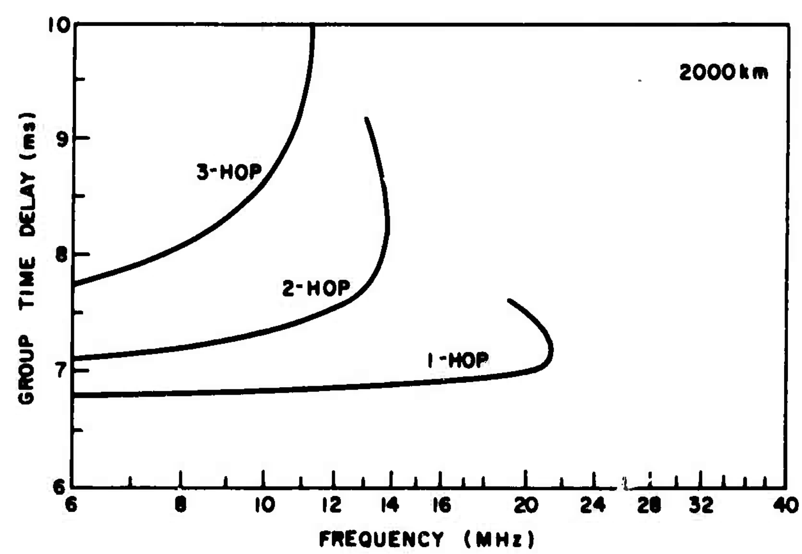
Calculations were performed to determine the rate of change (with frequency) in polarization angle as a function of frequency and geomagnetic azimuth. A digital computer raytracing program developed by Croft [Ref. 4] was employed using the quasi-longitudinal approximation. The program input consists of ionospheric electron density vs height, takeoff elevation angle and azimuth of transmitted rays, transmitted frequency, and transmitter latitude. The output consists of total polarization rotation for the ground range at which each ray hits the earth. Elevation angles for each frequency are chosen so that the transmitted rays land in the neighborhood of a fixed ground range; the Faraday rotation at that ground range can then be determined by interpolation. By performing the calculations for many frequencies, polarization rotation as a function of frequency for one-hop communication is found. In addition to the polarization rotation information, the computer also calculates the no-field group and phase time delays incurred by each ray.

The number of polarization rotations executed by a one-hop signal as it travels from the transmitter into the ionosphere and reflects back to a receiver on the ground was determined as a function of frequency for rays transmitted at an azimuth of 45° east of magnetic north, and as a function of azimuth for 10.5 and 17.5 MHz. All calculations were made assuming transmitter location at a latitude of 38° and a receiver location at 2000-km ground range from the transmitter. The concentric, single-layer Chapman ionosphere that was employed is shown in Fig. 1 together with the corresponding 2000-km, computer-generated oblique ionogram [Ref. 5]. The vertical critical frequency was 9 MHz, giving a path maximum usable frequency of about 21.5 MHz. A dipole approximation to the earth's magnetic field aligned with geographic coordinates was employed.

Polarization rotation vs frequency for the 45° azimuth case is presented in Fig. 2, with the corresponding polarization rotation rate. Polarization rotation rates as a function of azimuth for 10.5 and 17.5 MHz are given in Fig. 3. The results are symmetric about the geomagnetic meridian. Figure 4 shows the corresponding phase time delay $(1/c \int \mu \, ds)$ vs frequency for the no-field case. The results indicate that the frequency rate of polarization angle increases with increasing frequency and with the

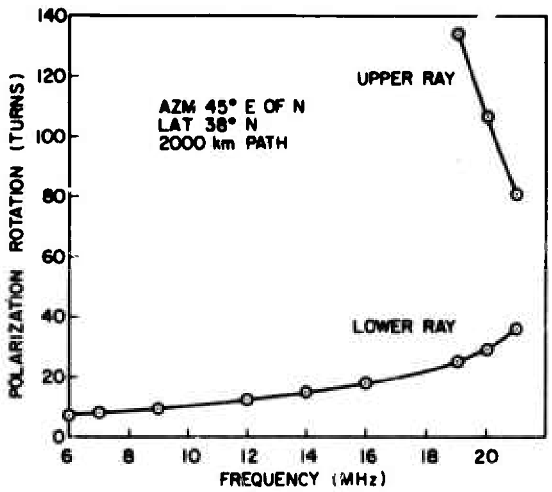


a. Electron density profile

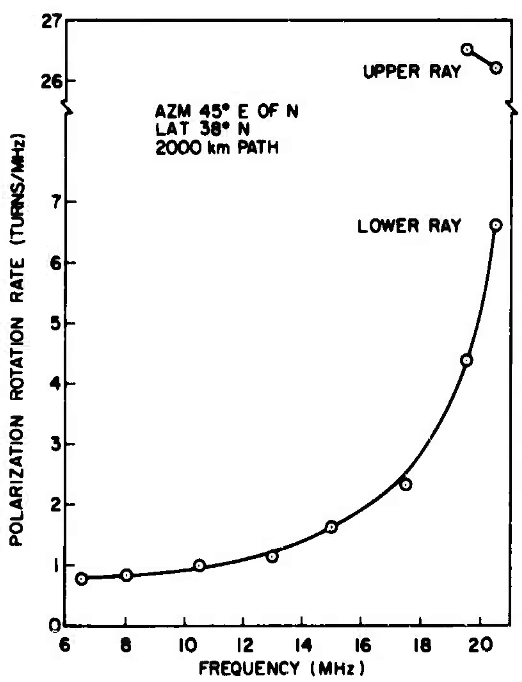


b. Corresponding 2000-km, computer-generated oblique ionogram

FIG. 1. IONOSPHERIC MODEL.



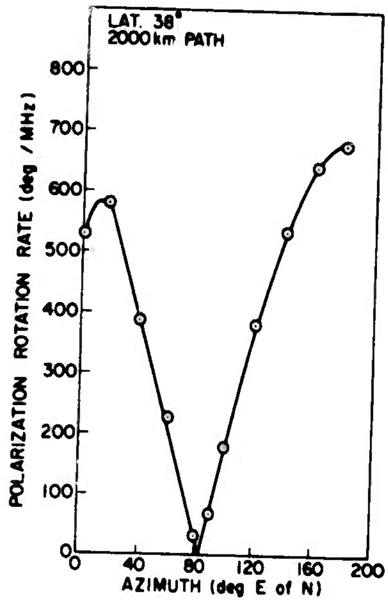
a. Polarization rotation



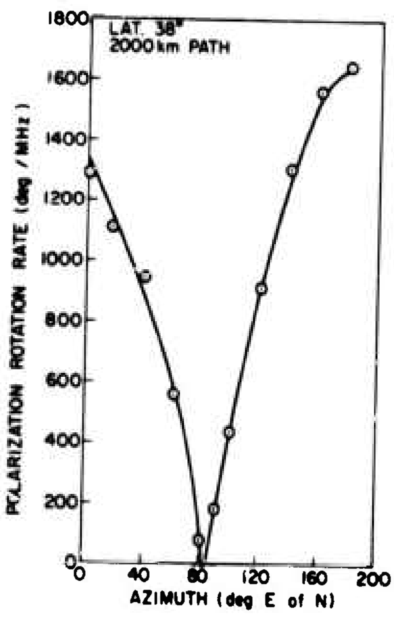
b. Polarization rotation rate

FIG. 2. POLARIZATION ROTATION AND POLARIZATION ROTATION RATE, AS A FUNCTION OF FREQUENCY.

longitudinal component of the earth's magnetic field along the raypath. The phase time delay varies almost linearly at 5.7 μs/MHz for 10.5 MHz and at 7 μs/MHz for 17.5 MHz.

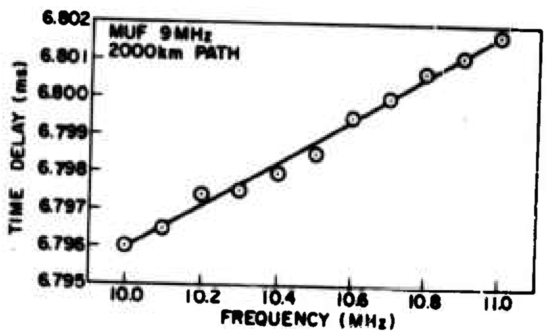


a. 10.5 MHz

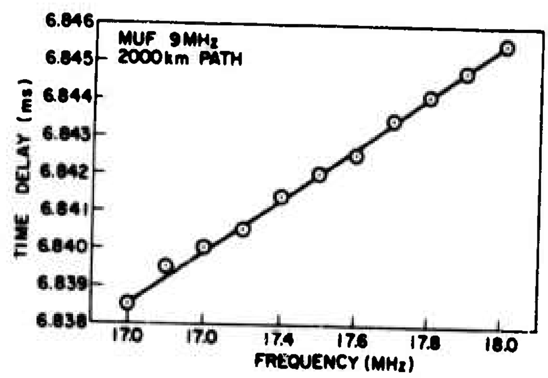


b. 17.5 MHz

FIG. 3. POLARIZATION ROTATION RATE AS A FUNCTION OF AZIMUTH. Azimuth indicates receiver location relative to transmitter.



a. 10.5 MHz



b. 17.5 MHz

FIG. 4. PHASE TIME DELAY AS A FUNCTION OF FREQUENCY.

III. THE EFFECT OF POLARIZATION ROTATION WITH FREQUENCY ON SHORT PULSES TRANSMITTED OVER AN IONOSPHERIC PATH

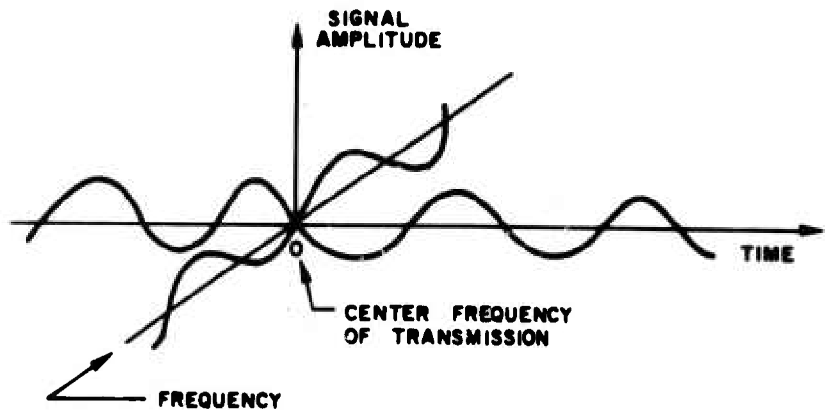
In order to evaluate the effect of the amplitude-frequency variation of signal strength due to the rotation of polarization with frequency, computations were performed to determine the received envelope of short-pulse signals after one-hop ionospheric passage. The ionospheric model employed in the calculations included phase time delay vs frequency (Fig. 4) and the amplitude vs frequency due to polarization rotation (Fig. 3) if the signal was received on a linearly polarized antenna. The results were obtained with a digital computer which evaluated the following Fourier integral, transforming from the frequency domain to the time domain:

$$\text{Output }(t) = \int \text{input }(f)\ \exp[j2\pi f(t - \tau(f))]\ A(f)\ df$$

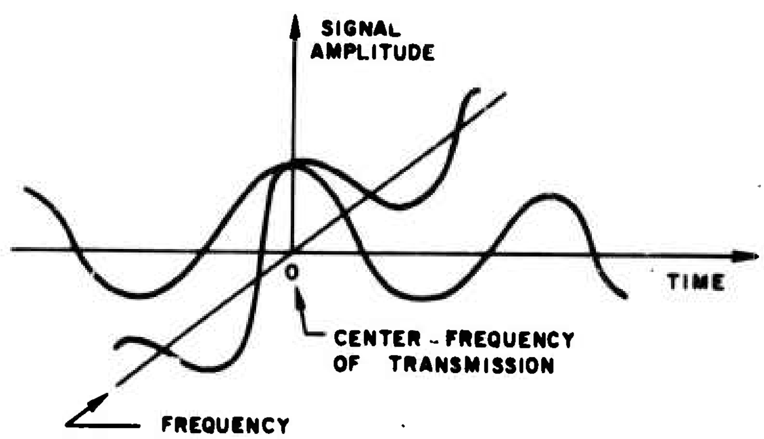
The argument of the integral, input(f)--the transform of the input pulse--is multiplied by an exponential phase factor $\tau(f)$ which shifts each of the component frequencies by the appropriate time delay. This is further multiplied by an amplitude factor $A(f)$ to describe the effects of polarization rotation vs frequency. (See note on p. 20.)

Two cases of amplitude-frequency distortion are considered. The first assumes that the center frequency of the transmitted pulse coincides with a cross-polarized frequency; the second assumes that the center frequency coincides with a parallel-polarized frequency. The former produces an amplitude null at the center frequency and, in general, produces more distortion than the latter. Both possibilities are equally likely at an instant of time as the amplitude at the center frequency varies--with time--according to polarization rotation with time. The two cases are illustrated in Fig. 5.

Gaussian-shaped RF pulse envelopes of 0.5, 1.5, 5, and 50 μs duration (3 db width) were considered (Figs. 6-12). Figures 6, 7, 9, and 10 show these envelope shapes before and after ionospheric phase and amplitude distortion for a center frequency of 17.5 MHz and for azimuths of 17° and 90°. Data for 0.5-μs pulses with a center frequency of 10.5 MHz are given in Fig. 11.



a. Cross-polarized center frequency



b. Parallel-polarized center frequency

FIG. 5. EFFECTS OF POLARIZATION ROTATION WITH TIME AND FREQUENCY.

The time scale indicated for the output pulses in Figs. 6-7 and 9-12 does not include ionospheric transit time. The pulses are symmetric with respect to the ordinate axis because the phase time vs frequency characteristic employed in the calculations is linear.

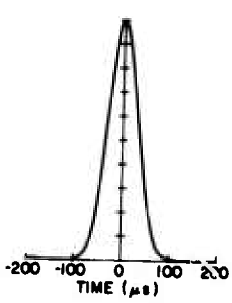
It is important to note that the pulse shapes in Figs. 6-7 and 9-12 represent RF pulse envelopes. Figure 8a shows the received RF pulse, and Fig. 8b shows the diode-detected envelope shape, corresponding to Fig. 7d.

A zero crossing of any pulse envelope indicates a 180° phase shift in the RF carrier signal.

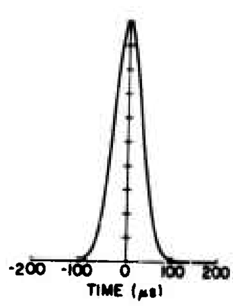
The 50-μs pulse incurs negligible distortion from the phase and amplitude characteristics; the 5-μs pulse is only slightly distorted by the phase vs frequency characteristics, but is noticeably further distorted by the amplitude-frequency characteristic. Significant distortion and spreading to about twice the original duration are introduced by phase distortion for the 1.5-μs pulse. Either case of polarization rotation with frequency renders the pulse shape almost unrecognizable and results in a fourfold pulse-duration increase.

The results for the 0.5-μs pulse follow the trend of more severe distortion for larger signal bandwidths. In this situation, the primary effect of the polarization rotation on the already time-spread pulse (20 to 1 spread) is to severely distort the pulse and also to produce the appearance of more than one pulse.

Calculations were also performed to determine the distortion incurred by a 0.5-μs pulse due to polarization rotation over a path with no phase distortion. The results, presented in Fig. 12, indicate that it is especially important to consider the effects of polarization rotation with frequency over low-phase-distortion paths. The noticeable "split pulse" results from a splitting of the pulse's spectrum by the amplitude-frequency characteristic.

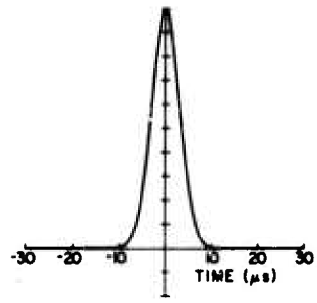


a. Input

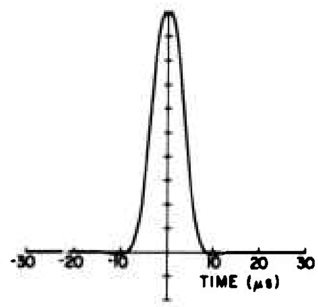


b. Output, phase distortion only

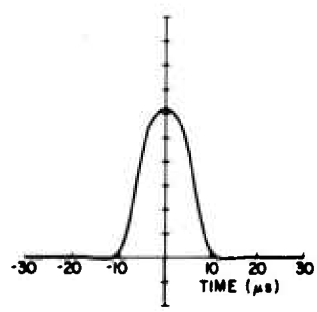
FIG. 6. ENVELOPE SHAPE OF IONOSPHERICALLY PROPAGATED 50-μs, 17.5-MHz PULSES BEFORE AND AFTER IONOSPHERIC PASSAGE.



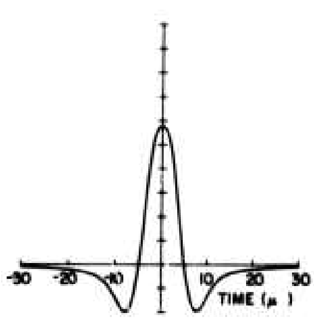
a. Input



b. Output, phase distortion only

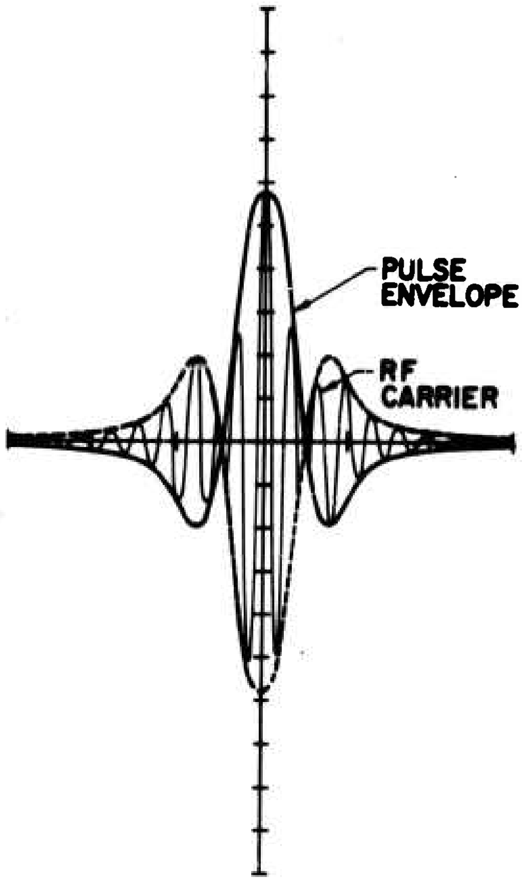


c. Output, phase distortion and parallel-polarized polarization distortion (17° azimuth)

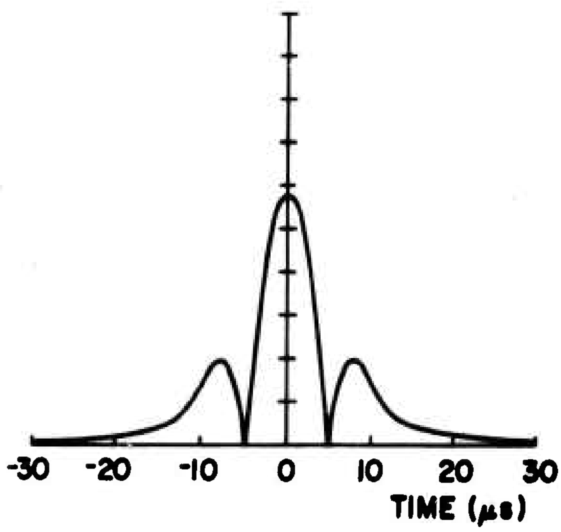


d. Output, phase distortion and cross-polarized polarization distortion (17° azimuth)

FIG. 7. ENVELOPE SHAPE OF IONOSPHERICALLY PROPAGATED 5-μs, 17.5-MHz PULSES BEFORE AND AFTER IONOSPHERIC PASSAGE.

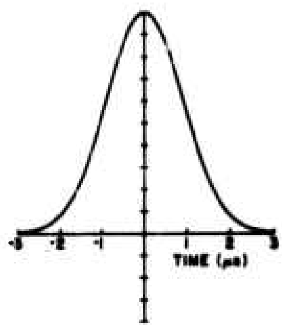


a. Pulse envelope shape with RF carrier

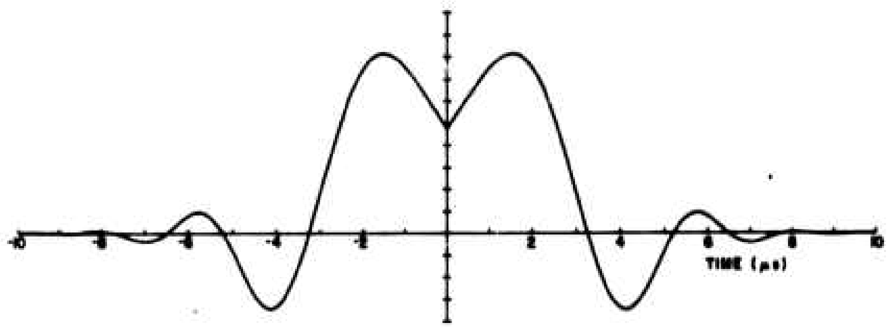


b. Diode-detected pulse

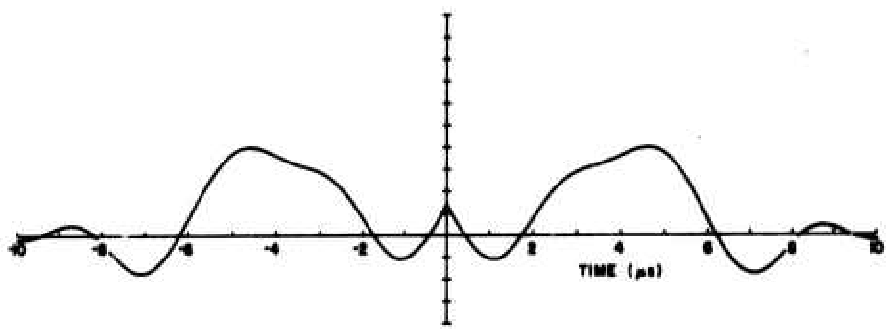
FIG. 8. RF PULSE WITH DIODE-DETECTED OUTPUT.



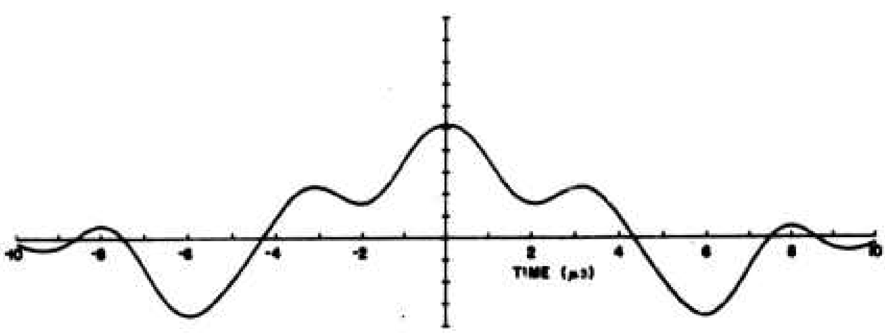
a. Input



b. Output, phase distortion only

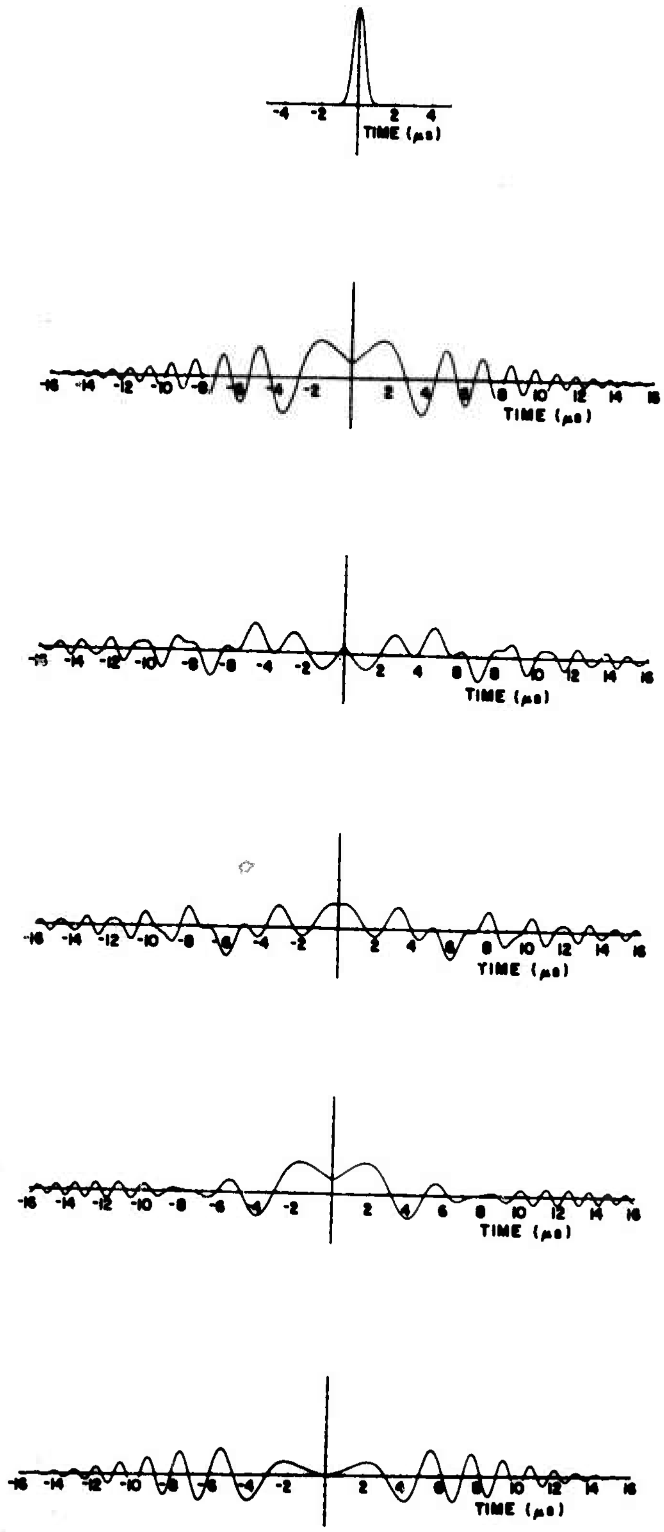


c. Output, phase distortion and parallel-polarized polarization distortion (17° azimuth)



d. Output, phase distortion and cross-polarized polarization distortion (17° azimuth)

FIG. 9. ENVELOPE SHAPE OF IONOSPHERICALLY PROPAGATED 1.5-μs, 17.5-MHz PULSES BEFORE AND AFTER IONOSPHERIC PASSAGE.



a. Input

b. Output, phase distortion

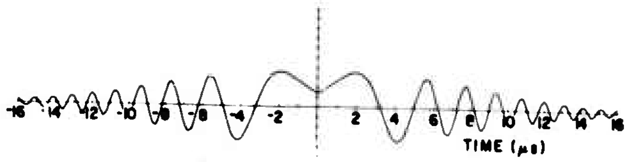
c. Output, phase distortion and parallel-polarized polarization distortion (17° azimuth)

d. Output, phase distortion and cross-polarized polarization distortion (17° azimuth)

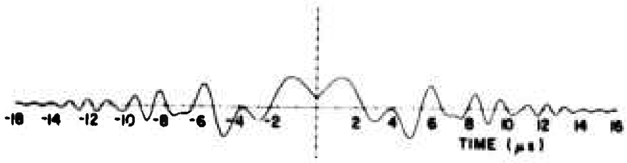
e. Output, phase distortion and parallel-polarized polarization distortion (90° azimuth)

f. Output, phase distortion and cross-polarized polarization distortion (90° azimuth)

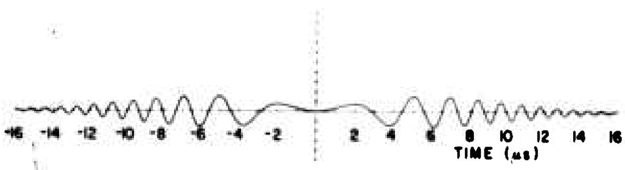
FIG. 10. ENVELOPE SHAPE OF IONOSPHERICALLY PROPAGATED 0.5-μs, 17.5-MHz PULSES BEFORE AND AFTER IONOSPHERIC PASSAGE.



a. Output, phase distortion

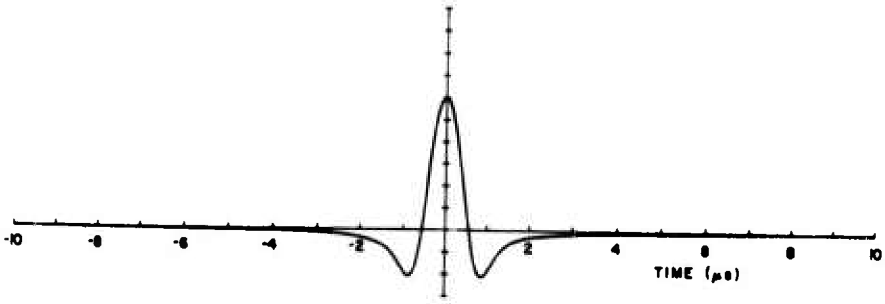


b. Output, phase distortion and cross-polarized polarization distortion (17° azimuth)

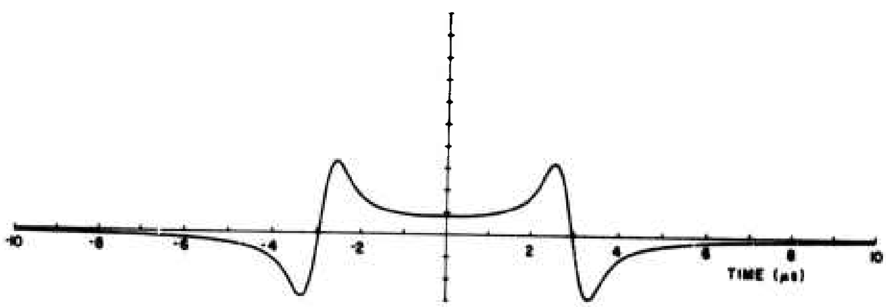


c. Output, phase distortion and cross-polarized polarization distortion (90° azimuth)

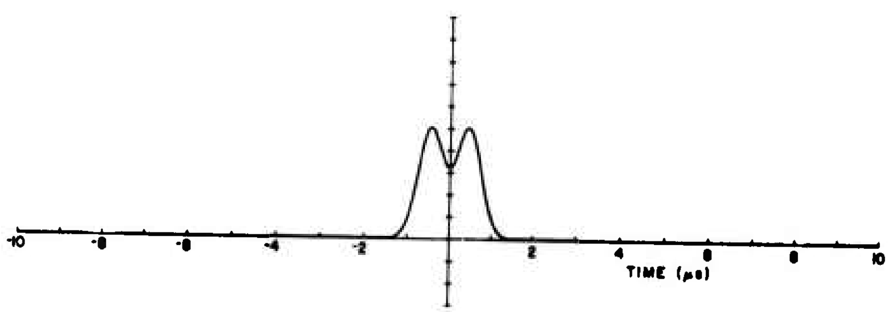
FIG. 11. ENVELOPE SHAPE OF IONOSPHERICALLY PROPAGATED 0.5-μs, 10.5-MHz PULSES AFTER IONOSPHERIC PASSAGE.



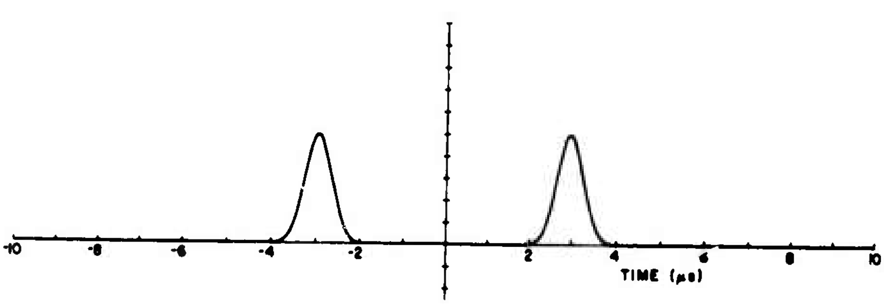
a. Cross-polarized polarization distortion (90° azimuth)



b. Cross-polarized polarization distortion (17° azimuth)



c. Parallel-polarized polarization distortion (90° azimuth)



d. Parallel-polarized polarization distortion (17° azimuth)

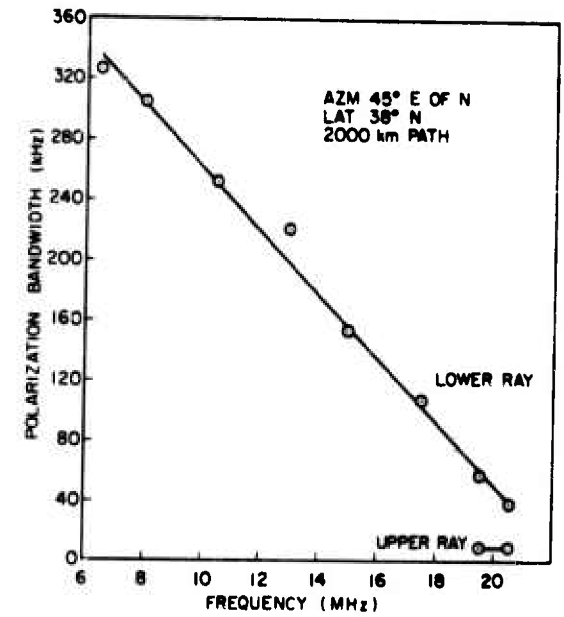
FIG. 12. SHAPE OF IONOSPHERICALLY PROPAGATED 0.5-μs PULSES OVER NO-PHASE-DISTORTION PATHS.

IV. DISCUSSION

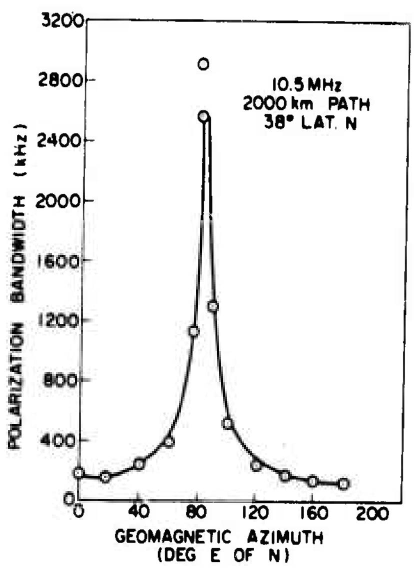
The results presented in Section III raise the question of how wide a bandwidth can be transmitted over a given ionospheric communications path before waveform distortion due to polarization rotation with frequency becomes critical. Although a complete answer to this question is a function of the type of signal employed and the waveform reproduction desired, a figure of merit is here defined. The effects of polarization rotation appear when the incoming polarization varies more than 90^0 over the signal bandwidth. This is the minimum bandwidth at which a communications link designer might begin to consider the effects of the polarization rotation with frequency. This bandwidth may be called the coherent polarization bandwidth. Coherent bandwidths as a function of frequency and azimuth are presented in Fig. 13 for the 2000-km one-hop path considered in Section II.

Two techniques that might be employed to eliminate the amplitude effects of polarization rotation with both time and frequency are (1) frequency diversity, and (2) the use of a circularly polarized antenna (which receives only one magnetoionic component). Two other techniques are useful in eliminating the effects produced by polarization rotation with time, but <u>not</u> with frequency; these are (3) polarization diversity, and (4) spaced-antenna diversity. Technique (3), in which one output of two orthogonal linearly polarized antennas is selected on the basis of signal strength, will not eliminate the amplitude-frequency effects because the signal on each antenna will be distorted. Technique (4) may not be practical except for very long, high-frequency paths, as indicated by the following values of polarization rotation with ground range for a 2000-km path:

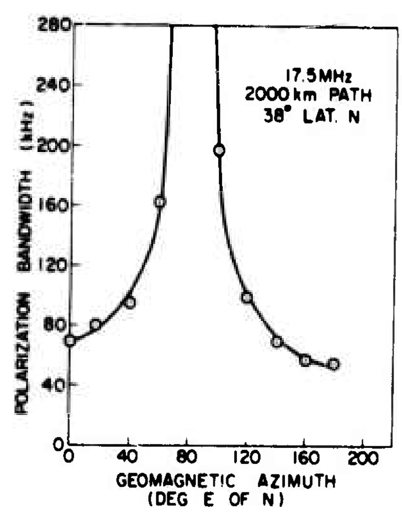
	Azimuth 90° E of N (deg/20 km)	Azimuth 17° E of N (deg/20 km)
10-11 MHz	4	33
17-18 MHz	4	140



a. As a function of frequency



b. As a function of azimuth at 10.5 MHz



c. As a function of azimuth at 17.5 MHz

FIG. 13. COHERENT POLARIZATION BANDWIDTHS.

V. CONCLUSIONS

It has been shown that where waveform preservation is important the effect of polarization (Faraday) rotation with frequency is to impose a bandwidth limitation on radio signals transmitted over a given skywave path and received on linearly polarized antennas. A measure of this limitation is here introduced as coherent polarization bandwidth, which is defined as the signal bandwidth across which the incoming signal polarization will vary 90^{o}--the threshold at which polarization effects become apparent.

Computations were performed to determine the coherent polarization bandwidth as a function of frequency and azimuth for a 2000-km Chapman-layer path which had a maximum usable frequency of 21.5 MHz. The size of the coherent bandwidth was found to decrease with frequency, path length, and alignment of the propagation path with the longitudinal component of the earth's magnetic field. Coherent bandwidths increased from 70 kHz at 17.5 MHz and from 140 kHz at 10.5 MHz, as the propagation direction varied from geomagnetic north to east. If pulse signal bandwidths larger than the coherent bandwidth for the path are employed, envelope distortion occurs.

It was found theoretically that pulses of 50-μs duration transmitted at any azimuth over the above-described ionospheric path would not be affected by the amplitude vs frequency variations attributed to polarization rotation with frequency; 5-μs pulses were affected as a function of azimuth, the amount of the distortion being a function of the instantaneous alignment of the incoming polarization with respect to the receiving antenna. The 0.5-μs and 1.5-μs pulses were very distorted in all cases considered.

REFERENCES

1. D. A. Hedlund and L. C. Edwards, "Polarization Fading over an Oblique Incidence Path," IRE Trans. on Antennas and Propagation, AP-6, 1, Jan 1958.

2. Gene C. Porter, "Measurement of Polarization Statistics of Signals Received over a Short Range HF Path," IEEE Trans. on Communication Technology, Com-14, 4, Aug 1966.

3. John M. Kelso, Radio Ray Propagation in the Ionosphere, McGraw- Hill Book Company, New York, 1964.

4. T. A. Croft, "Computed Faraday Rotation during Sporadic-E Propagation," Rept. SU-SEL-65-100 (TR No. 113, Contract Nonr-225(64)), Stanford Electronics Laboratories, Stanford, Calif., Oct 1965.

5. T. A. Croft, "Interpreting the Structure of Oblique Ionograms," Rept. SU-SEL-66-010 (TR No. 114, Contract Nonr-225(64)), Stanford Electronics Laboratories, Stanford, Calif., Feb 1966.

NOTE: The integral on p. 8, which relates the input and output of an (assumed) linear ionospheric transmission path, incorporates a single pair of amplitude and phase terms which taken together represent a transfer function which is equivalent to the sum of the transfer functions corresponding to the two magnetoionic components. It can be shown that this equivalent description takes into account the group path differences of the magnetoionic components even when, in the case of very short pulses, the magnetoionic components arrive at the receiver separated in time (see Fig. 12c, d). The group delay difference and amplitude effects due to polarization (which are equivalent parameters) are contained in the $A(f)$ term.

Discussion of results of experimental measurements of polarization rotation with frequency will appear in a future technical report.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Stanford Electronics Laboratories Stanford, California	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

COMPUTER PREDICTION OF THE EFFECTS OF HF OBLIQUE-PATH POLARIZATION ROTATION WITH FREQUENCY

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Technical Report

5. AUTHOR(S) *(First name, middle initial, last name)*

M. R. Epstein

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
February 1967	20	5

8a. CONTRACT OR GRANT NO. Nonr-225(64), NR 088 019 b. PROJECT NO. ARPA Order 196-67 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) SU-SEL-67-026 Technical Report No. 139 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

This document is subject to special export controls and each transmittal to foreign governments or foreign nations may be made only with prior approval of the Office of Naval Research, Field Projects Branch, Washington, D.C., 20360.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U.S. Navy, Office of Naval Research Advanced Research Projects Agency

13. ABSTRACT

When a CW skywave signal is received on a linearly polarized antenna, polarization (Faraday) rotation produces a variation of received signal strength with radio frequency. The resulting dependence of received signal amplitude on radio frequency imposes a bandwidth limitation on pulsed signals transmitted over ionospheric paths. A measure of this limitation, termed "coherent polarization bandwidth," is defined to correspond to the bandwidth in which the plane of polarization rotates 90°.

Computer raytracing calculations were performed using a single Chapman-layer ionospheric model to determine the one-hop coherent polarization bandwidth as a function of geomagnetic azimuth and frequency. The coherent bandwidth was found to decrease with increasing path length, radio frequency, and geomagnetic azimuth. Assuming a critical frequency of 9 MHz and a path length of 2000 km, the bandwidth increased from a minimum of 140 kHz at 10.5 MHz and from a minimum of 70 kHz at 17.5 MHz as the propagation direction varied from geomagnetic north to east.

The theoretical effects of polarization rotation with frequency, and also of ionospheric dispersion or phase distortion, on the envelope shape of short-pulse signals (of from 0.5 to 50 μs duration) were calculated by computer for the same path. A pronounced waveshape distortion due to the effect of polarization rotation on the pulse envelope was observed when the signal bandwidth appreciably exceeded the coherent polarization bandwidth for the path.

DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
HF COMMUNICATIONS						
FARADAY ROTATION						
POLARIZATION						